REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1/12/97

3. REPORT TYPE AND DATES COVERED
FINAL REPORT

4. TITLE AND SUBTITLE
Dynamic Behavior of Brittle Materials

5. FUNDING NUMBERS
DAAL03-92-K-0002

6. AUTHOR(S)
Professor SiaNemat-Nasser

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Center of Excellene for Advanced Materials
Dept of Applied Mechanics and Engineering Sciences
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0416

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30351.9-MS

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The program focused on a fundamental study of the dynamic response and failure modes of a broad class of conventional and advanced brittle materials. The initial five-year research program addressed materials of current interest to the Army (titanium diboride, titanium carbide, alumina silicon carbide, aluminum, nitride, zirconia, and silicon nitride), as well as novel materials and concepts (nanocrystalline ceramics, laminated and fiber reinforced ceramic composites, functionally graded materials). However, only funding of the first year and partial funding of the second year were received. Hence, limited specific programs were developed in a multi-disciplinary mode, encompassing experimental, analytical, and microstructural characterization components. Through testing and analysis, physically-based constitutive models were developed.

14. SUBJECT TERMS
High-Strain -Rate
Penetration
Ceramics

15. NUMBER IF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Dynamic Behavior of Brittle Materials

FINAL TECHNICAL REPORT

PROFESSOR SIA NEMAT-NASSER

JANUARY 1997

US ARMY RESEARCH OFFICE
DAAL-03-92-K-0002

UNIVERSITY OF CALIFORNIA, SAN DIEGO

I. STATEMENT OF PROBLEM STUDIED

The program focused on a fundamental study of the dynamic response and failure modes of a broad class of conventional and advanced brittle materials. The initial five-year research program addressed materials of current interest to the Army (titanium diboride, titanium carbide, alumina silicon carbide, aluminum, nitride, zirconia, and silicon nitride), as well as novel materials and concepts (nanocrystalline ceramics, laminated and fiber reinforced ceramic composites, functionally graded materials). However, only funding of the first year and partial funding of the second year were received. Hence, limited specific programs were developed in a multi-disciplinary mode, encompassing experimental, analytical, and microstructural characterization components. Through testing and analysis, physically-based constitutive models were developed. The basic program included: 1) microstructural characterization of the material at various stages of deformation, using state-of-the-art microscopy facilities at UCSD; 2) dynamic recovery experiments over a broad range of strain rates, from quasi-static to 10^6/s and greater, in compression, tension, and combined compression/shear deformation modes, employing the unique facilities and experimental techniques for recovery tests, currently existing at UCSD's Center of Excellence for Advanced Materials (CEAM); 3) development of mathematical micromechanical models which most concisely and rigorously captured the basic physics of the micromechanisms involved in damage initiation and evolution by inelastic deformation and microcracking, including possible compression-induced fracturing, microcrack interaction and coalescence, and fragmentation; 4) development of micromechanically-based constitutive models for implementation in large-scale computer codes, and, equally important, construction of efficient and robust computational algorithms which consistently, accurately, and effectively integrate the constitutive relations in a large-scale computational environment necessary for the analysis and prediction of dynamic deformation and failure modes, using state-of-the-art supercomputing and parallel-processing facilities; and 5) delineation of the damage initiation and evolution in ceramics subject to dynamic loading by plate impact or through a penetrator.

II. SUMMARY OF MOST IMPORTANT RESULTS

- **Pressure-Shear Recovery Experiments** by A. Machcha and S. Nemat-Nasser

  Results of successful pressure-shear place impact recovery experiments is reported. The technique makes use of flyer configuration involving two plates which are separated by a thin lubricant layer, and a target assembly consisting of a specimen backed by a momentum trap. This enables the recovery of the specimen that has been subjected to combined longitudinal and transverse loading pulses. A small amount of residual shear, equal to the shear strength of the lubricant, cannot be eliminated. The transmitted stress waves have been measured using interferometry.

- **Effects of Geometry in Pressure-Shear and Normal Plate Impact Recovery Experiments: Three-Dimensional Finite-Element Simulation and Experimental Observation** by Ashok Machcha and Sia Nemat-Nasser

  The minimization of the radial release effects in the recovery configurations of plate impact experiments is essential for accurate postmortem microstructural investigations. The present study evaluates the results of several three-dimensional finite-element simulations involving different plate geometries. The study examines combinations of circular, square, and star-shaped plate geometries, with no lateral momentum traps or guard rings. Experiments and simulations are conducted on brittle specimens. A simple, but fairly successful, combination for the pressure-shear recovery experiment is reported, which makes use of a single square and three circular plates. In the case of the normal impact recovery configuration, it is found that the star-shaped flyer in combination with the square target and momentum trap gives good results at locations

away from the axis of the specimen. Crack patterns observed experimentally in the conventional nonrecovery pressure-shear mode, and in recovery pressure-shear and normal impact modes are discussed in relation to the simulation results.

- **Strain-Rate Effect on Brittle Failure in Compression** by Sia Nemat-Nasser and Hang Deng

A simple model of an array of interacting, dynamically growing wing cracks is used to simulate the rate-dependent dynamic damage evolution and subsequent brittle failure of solids under compression. The validity of the model is discussed. Parameters which identify the overall failure by the coalescence of compression-induced, interacting, tensile microcracks are calculated in closed form, and relations between microstructure and the corresponding rate dependency of the overall response are examined in some detail. It is shown that the experimentally observed change in the compressive failure stress with increasing strain rate, may be considered to be a consequence of the generation and dynamic growth of interacting, compression-induced, tensile microcracks. Examples of brittle failure in uniaxial stress and uniaxial strain conditions, respectively, produced in the Hopkinson compression bar and normal plate-impact experiments, are discussed in terms of this model.

- **Microcrack Interaction and Shear Fault Failure** by Hang Deng and Sia Nemat-Nasser

The method of pseudo-tractions is used to solve the problem of interacting cracks which are arbitrarily distributed and are loaded by concentrated forces. The effect of interaction on the crack tip stress intensity factors is obtained for a set of equally spaces, parallel cracks which are loaded by both concentrated forces and uniform farfield stresses. For the special case when the cracks are collinear, the results are compared with those of the closed-form exact solution to check the accuracy of the method. The method is then applied to an array of dynamically growing wing cracks, and the growth regime of a periodic array of wing cracks of arbitrary orientation is studied. The shear fault failure mechanism is discussed in terms of such a model. The direction of the shear fault is related to the direction of a periodically distributed wing-crack array, in which tension cracks grow to length equal to their spacing at a minimum applied load. The effect of confining pressure on the shear fault direction is discussed.

- **Dynamic Damage Evolution of Solids in Compression: Microcracking, Plastic Flow, and Brittle-Ductile Transition** by Hang Deng and Sia Nemat-Nasser

Dynamic compressive damage evolution in solids, associated with brittle micro cracking and ductile plastic flow, is modeled through plastic flow and tensile microcracking, which are induced by the deformation of preexisting microflaws at grain boundaries, slip bands, and microcavities. The micromechanical aspect of this model is discussed in terms of the dominance of microcracking or plastic flow, and possible transition from microcracking to plastic flow is investigated. The effect of lateral confinement on the dynamic damage evolution is investigated, emphasizing the brittle-ductile transition.

- **An Efficient Algorithm for Viscoplastic Flow of Granular Materials** by B. Balendran and Sia Nemat-Nasser

A constitutive model is developed for granular materials, in which the inelastic deformation consists of dilatancy and deviatoric strains. Possible strong pressure and strain rate sensitivity of the flow stress is included. The effect of fabric anisotropy is also incorporated. An efficient numerical algorithm is presented for incremental integration of this class of constitutive equations, when the increment deformation gradient is prescribed. The effectiveness of this algorithm is illustrated.

- **Bounds on Elastic Moduli of Composites** by B. Balendran and Sia Nemat-Nasser

General computable bounds are developed for the stored elastic energy of a finite-sized sample of heterogeneous material which consists of a matrix containing disconnected inclusions which may themselves be heterogeneous. These bounds also apply to the limiting cases of elastic solids with disconnected cavities or rigid inclusions. The lower bounds for solids with cavities are nonzero, and the upper bounds for solids with rigid inclusions are finite. As an illustration. closed-form bounds are obtained for the overall elastic parameters of fiber reinforced composites. The fiber packing may be triangular. square, or hexagonal. Though the results are presented for fibers with hexagonal cross sections, the closed-form expressions also apply to arbitrarily shaped cross sections. The general procedure also applies to nonlinear heterogeneous solids which possess convex strain and stress potentials.

- **Overall Properties of Elastic Viscoplastic Periodic Composites**
by Peter A. Fotiu and Sia Nemat-Nasser

The assumption of a periodic distribution of inclusions gives accurate estimates of the overall moduli of composites, especially when interactions among inclusions are dominant. In this paper periodic composites with rate-dependent elastic-plastic material response including non linear power-law hardening are considered. Overall stress-strain relations are obtained and the dependence of these relations on the density of the discretization of the unit cell is studied. Several options, such as the use of mirror image symmetry/antisymmetry, partially analytic summation of Fourier series, and a highly accurate and stable time-integration algorithm help to keep the computational expense low. The formulation is presented in three dimensions as well as for plane-stress and plane-strain problems.

- **Universal Bounds for Overall Properties of Linear and Non Linear Heterogeneous Solids** by Sia Nemat-Nasser and Muneo Hori

For a sample of a general heterogeneous nonlinearly elastic material, it is shown that, among all consistent boundary data which yield the same overall average strain (stress), the strain (stress) field produced by uniform boundary tractions (linear boundary displacements), renders the elastic strain (complementary strain) energy an absolute minimum. Similar results are obtained when the material of the composite is viscoplastic. Based on these results, universal bounds are presented for the overall elastic parameters of a general, possibly finite-sized, sample of heterogeneous materials with arbitrary microstructures, subjected to any consistent boundary data with a common prescribed average strain or stress. Statistical homogeneity and isotropy are neither required nor excluded. Based on these general results, computable bounds are developed for the overall stress and strain (strain-rate) potentials of solids of any shape and inhomogeneity, subjected to any set of consistent boundary data. The bounds can be improved by incorporating additional material and geometric data specific to the given finite heterogeneous solid. Any numerical (finite-element or boundary-element) or analytical solution method can be used to analyze any subregion under uniform boundary tractions or linear boundary displacements, and the results can be incorporated into the procedure outlined here, leading to exact bounds. These bounds are not based on the equivalent homogenized reference solid (discussed in Sections 3 and 4). They may remain finite even when cavities or rigid inclusions are present. Complementary to the above-mentioned results, for linear cases, eigenstrains and eigenstresses are used to homogenize the solid, and general exact bounds are developed. In the absence of statistical homogeneity, the only requirement is that the overall shape of the sample be either parallelepipedic (rectangular or oblique) or ellipsoidal, though the size and relative dimensions of the sample are arbitrary. Then, exact analytically computable, improvable bounds are developed for the overall moduli and

compliances, without any further assumptions or approximations. Bounds for two elastic parameters are shown to be independent of the number of inhomogeneity phases, and their sizes, shapes, or distribution. These bounds are the same for both parallelepipedic and ellipsoidal overall sample geometries, as well as for the statistically homogeneous and isotropic distribution of inhomogeneities. These bounds are therefore universal. The same formalism is used to develop universal bounds for the overall non-mechanical (such as thermal, diffusional, or electrostatic) properties of heterogeneous materials.

- **Effect of Grain Boundary Phase on Dynamic Compression Fatigue in Hot Pressed Silicon Nitride** by Vinod Sharma, Sia Nemat-Nasser, and Kenneth S. Vecchio

Two types of hot-pressed silicon nitrides, one having an amorphous grain-boundary phase (6 wt% yttria, 3 wt% alumina) and the other having a predominantly crystalline grain boundary phase (8 wt% yttria, 1 wt% alumina) were tested on a split Hopkinson pressure bar with a momentum trap, such that, in each test, the sample is subjected to a single predefined stress pulse and then recovered without being subjected to any other loads. The specimens were loaded repeatedly with a triangular pulse of 3.2 GPa amplitude at a strain rate of approximately 400/sec. The dynamic fatigue life of amorphous grain-boundary phase silicon nitride was observed to be higher than that of the corresponding fatigue life of crystalline grain-boundary phase silicon nitride. The difference in fatigue lives is correlated to the microstructural damage occurring in both materials.

- **Modeling the Strain Rate Dependence of Fatigue Life of Hot Pressed Silicon Nitride** by Vinod Sharma, Sia Nemat-Nasser, and Kenneth S. Vecchio

This paper presents the results of a micromechanical model used to explain the strain rate dependence of the compression fatigue lives of amorphous and crystalline grain-boundary phase silicon nitrides; denoted by ABP and CBP silicon nitrides, respectively. When the strain rate is changed from 400/s to 0.01/s, the fatigue lives of both materials, evaluated at a peak stress of 3.2 GPa, increased by more than two orders of magnitude (Sharma et al., 1996 a, b). The model is based on the dynamic and quasi-static microstructural damage mechanisms observed in both materials. The microstructure of ABP and CBP silicon nitrides is modeled as a simple composite in which silicon nitride grains are embedded in a continuous network of the grain boundary phase. Since the subsurface fatigue cracks in both materials nucleate mainly from the contact region between silicon nitride grains, contact stresses between adjacent silicon nitride grains are obtained, and the frequency dependence of the fatigue lives of ABP and CBP silicon nitrides is explained on the basis of the strain-rate sensitivity of the grain-boundary phase

- **Damage Evolution in Hot-Pressed Silicon Nitride Under Quasi-Static Compression Fatigue** by Vinod Sharma, Sia Nemat-Nasser and Kenneth S. Vecchio

This paper presents the results of an investigation of the effect of the grain-boundary phase on the quasi-static compression fatigue of hot-pressed silicon nitride. Amorphous and crystalline grain boundary phase silicon nitrides were tested at a peak stress of 3.2 GPa, and at strain rates of 0.1/s and 0.01/s. The number of cycles to failure for both types of silicon nitrides was essentially similar at a strain rate of 0.01/s, suggesting that the grain boundary phase plays a minor role in determining the quasi-static compression fatigue life of hot-pressed silicon nitride. The role of the grain boundary phase was further confirmed by examining damage evolution via electron microscopy and ultrasonic wave-speed measurements. The fatigue lives of amorphous and crystalline grain boundary phase silicon nitrides, at a peak stress of 3.2 GPa, was observed to be more than two orders of magnitude greater at a strain rate of 0.01/s than that at a strain rate

of 400/s. The difference in the fatigue lives, for either of the materials, is attributed to the strain rate-dependent damage mechanisms and the corresponding amount of energy used, per cycle, to generate defects in amorphous and crystalline grain boundary phase silicon nitrides.

III. LIST OF PUBLICATIONS

The following manuscripts, submitted for publication, in press, and published, were prepared wholly or partially under the sponsorship of the Army Research Office, DAAL 03-92-K-0002.

A. Published Manuscripts

"An Efficient Algorithm for Viscoplastic Flow of Granular Materials," Balendran, B., and S. Nemat-Nasser, Presented at the ASME WAM, New Orleans, Nov. 28-Dec. 7, 1993, *Advances in Numerical Simulation Techniques for Penetration and Perforation of Solids*, edited by E.P. Chen and V.K. Luk, AMD Vol. 171 (1993), 111-124. (also supported by AFOSR F49620-92-J-0117 to UCSD)

"Strain-Rate Effect on Brittle Failure in Compression," Nemat-Nasser, S. and H. Deng, *Act a Metallurgica et Materialia, Vol.* 42, No. 3 (1994), 1013-1024. (also supported by ARO DAAL-03-86-K-0169 to UCSD)

"Microcrack Interaction and Shear Fault Failure," Deng, H. and S. Nemat-Nasser, *International .lournal of Damage Mechanics,* Vol. 3, No. 1 (1994), 3-37. (also supported by ARO DAAL-03-86-K-0169 to UCSD)

"Pressure-Shear Recovery Experiments," Machcha, A. and S. Nemat-Nasser, *Mechanics of Materials*, Vol. 18 (1994), 49-53. (also supported by ARO DAAL-03-86-K-0169 to UCSD)

"Double-Inclusion Model and Overall Moduli of Multi-Phase Composites," Hori, M. and S. Nemat-Nasser, *Journal of Engineering Materials and Technology,* Vol. 116 (1994), 305-309.

"Dynamic Damage Evolution of Solids in Compression: Microcracking, Plastic Flow, and Brittle-Ductile Transition," Deng, H. and S. Nemat-Nasser, *Journal of Engineering Materials and Technology,* Vol. 116, (1994) 286-289. (also supported by ARO DAAL-03-86-K-0169 to UCSD and NSF (CRAY Y-MP))

"A Duality Principle and Correspondence Relations in Elasticity," Nemat-Nasser, S. and L. Ni, Special Issue *Journal of Solids and Structures,* Dundur Symposium at the 12th U.S. National Congress of Applied Mechanics, June 27-July 1, 1994, Vol. 32, No. 3/4 (1995) 467-472.

"Integration of Inelastic Constitutive Equations for Constant Velocity Gradient with Large Rotation," Balendran, B. and S. Nemat-Nasser, *Applied Mechanics and Computation,* Vol. 67 (1995) 161-195. (also supported by ARO DAAL-03-92-G-0108 to UCSD).

"Bounds on Elastic Moduli of Composites," Balendran, B. and S. Nemat-Nasser, *J. Mech. Phys. Solids*, Vol. 43, No. 11 (1995) 1825-1853.

"Universal Bounds for Overall Properties of Linear and Nonlinear Heterogeneous Solids," Nemat-Nasser, S. and M. Hori, Transactions of ASME, Vol. 117 (1995) 412-432. (also supported by ARO DAAL-03-92-G-0108 to UCSD).

"Overall Properties of Elastic-Viscoplastic Periodic Composites," Fotiu, P.A. and S. Nemat-Nasser, *Intl. J. of Plasticity*, Vol. 12, No. 2 (1996) 163-190. (also supported by ARO DAAL-03-92-G-0108 to UCSD).

"A General Duality Principle in Elasticity," Ni, L. and S. Nemat-Nasser, *Mechanics of Materials*, Vol. 24 (1996) 87-123.

"Hoop Stress Intensity Factor and Crack-Kinking in Anisotropic Solids," Azhdari, A., and S. Nemat-Nasser, *International Journal of Solids and Structures,* Vol. 33, No. 14 (1996) 2023-2037.

"Energy-Release Rate and Crack Kinking in Anisotropic Brittle Solids," Azhdari, A. and S. Nemat-Nasser, *J. Mech. Phys. Solids,* Vol. 44, No. 6 (1996) 929-951. (also supported in part by UCSD's Institute for Mechanics and Materials (IMM) and the San Diego Supercomputer Center's CRAY-YMP.

"Effects of Geometry in Pressure-shear and Normal Plate Impact Recovery Experiments: Three-Dimensional Finite-element Simulation and Experimental Observation," Machcha, A. and S. Nemat-Nasser, J. Appl. Physics, Vol. 80, No. 6 (1996). (also supported by NSF MSS-90-21671 for work performed on the CRAY-90 at San Diego Supercomputer, and ARO-DAAL-03-86-K-0169 to UCSD).

B. Manuscripts In-Press, Accepted, Submitted, or Work In-Progress

"Effect of Grain Boundary Phase on Dynamic Compression Fatigue in Hot Pressed Silicon Nitride," Sharma, V., S. Nemat-Nasser, and K. S. Vecchio, J. *of American Ceramic Society,* in-press 10/96 (also supported by ARO DAAL-03-86-K-0169 to UCSD).

"Fracturing in Anisotropic Brittle Solids: Theory and Some Preliminary Experimental Results," Nemat-Nasser, S. and A. Azhdari, *Proceedings of 14th U.S. Army Solid Mechanics Symposium,* October 16-18, 1996, in-press.

"Fracturing in an Anisotropic Brittle Solid (Sapphire)," Azhdari, A. and S. Nemat-Nasser, Special Issue of *Mechanics and Materials*, submitted 11/96.

"Modeling the Strain Rate Dependence of Fatigue Life of Hot Pressed Silicon Nitride", Sharma, V., S. Nemat-Nasser, and K. S. Vecchio, submitted to *Mechanics of Materials* special issue, 1/97. (also supported by ARO DAAL-03-86-K-0169 to UCSD, and the San Diego Supercomputer's CRAY-YMP)

"Damage Evolution in Hot-Pressed Silicon Nitride Under Quasi-Static Compression Fatigue", Sharma, V., S. Nemat-Nasser, and K. S. Vecchio, submitted to *Journal Materials Science Engineering*, 1/97.

"Micro- and Macro-Structural Damage Observations in Alumina Ceramics Under Pressure-Shear Impact Loading," Machcha, A., and S. Nemat-Nasser, work in-progress 10/96. (also supported by ARO DAAL-03-88-K-0169 to UCSD).

IV. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED

Scientific Personnel:

T. Impelluso (1/93-1/93) Postdoctoral Research Engineer. Research focused on computational mechanics, especially data management and visualization. *PI: G. Hegemier*

D.S. Kim (4/94-7/94) Postdoctoral Research Engineer. Research focused on showing the microscopic findings of shear band and it effect on the change in ultrasonic velocities of the W-Fe-Ni alloy. A specific task is designed to evaluate the physical-based material parameters which can be used for constitutive modeling. *PI: S. Nemat-Nasser (partial support).* Current Status: Engineer, Rural Development Corporation, Korea

B. Balendran (2/93 - June 1995) Postdoctoral Research Engineer. Research focuses on computational methods in granular flow and constitutive modeling high strain, high strain rate, high temperature experimental and computational modeling. *PI: S. Nemat-Nasser.* Current Status: Project Engineer, Lexel Engineering, Troy, MI

Y.F. Li (4/94 - 6/94) Postdoctoral Research Engineer. Research focused on computational modeling. *PI: S. Nemat-Nasser.* Current status: Project Section Leader, Joint Engineering Consultants, Taipei, Taiwan

H. Deng (2/93-9/93) Postdoctoral Research Engineer. Research focused on dynamic failure of ceramics. *PI: S. Nemat-Nasser.* Current status: Engineer, Allied Signal, Torrance, CA

P. Fotiu (2/93-7/93) Assistant Researcher. Research focused on computational modeling of heterogeneous materials. *PI: S. Nemat-Nasser.* Current status: Researcher at Institut für Allgemeine Mechanik, Technical University of Vienna

M. Beizaie (1/93 - 2/95) Assistant Researcher. Research focused on data acquisition and image processing by computer; composites. *PI: S. Nemat-Nasser (partial support).* Current Status: at UCSD CEAM supported by different funding.

L. Ni (12/94 - 6/95) Assistant Research Engineer. Research focused on duality principles and correspondence relations in elasticity. *PI: S. Nemat-Nasser (partial support).* Current Status: at UCSD CEAM supported by different funding.

Graduate Research Assistants:

V. Sharma (11/93-9/94) Research focused on modeling the strain-rate dependent compression fatigue behavior of silicon nitride *PI: S. Nemat-Nasser (partial support).* Current Status: Postgraduate Researcher at UCSD CEAM

A. Machcha (11/93-8/94) Research focused on dynamic behavior of alumina ceramics with different glass contents and simulations of plate-impact configuration in the pressure shear and normal impact modes. *PI: S. Nemat-Nasser (partial support).* Current Status: Research Scientist, Phase Metrics, San Diego, CA

A. Azhdari (10/93-9/94) Research focused on the study of which fracture criterion, maximum-KI, zero-KII, maximum-hoop stress, and maximum-energy-release-rate may predict the phenomenon of crack-kinking in anisotropic solids. Sapphire was used for the experimental part of the work. *PI: S. Nemat-Nasser (partial support).* Current Status: Postgraduate Researcher at UCSD CEAM.

W. Gu (10/94-6/95) Research focused on the microstructure of ceramics; silicon nitride and silicon carbide. *(PI: S. Nemat-Nasser)*

Degrees Awarded

V. Sharma, Ph.D. 9/94 Thesis: "Damage Evolution in Hot-Pressed Silicon-Nitride Under Repeated Dynamic and Quasi-Static Compression Loading"
(PI: S. Nemat-Nasser)
Current Status: Postgraduate Researcher at UCSD CEAM

A. Machcha, Ph.D. 9/94 Thesis: "Dynamic Response of Materials at High Loading Rates: Study on Ceramics and EHD Lubricants"
(PI: S. Nemat-Nasser)
Current Status: Research Scientist, Phase Metrics, San Diego, CA

V. REPORT OF INVENTIONS (BY TITLE ONLY): NONE